A 3-D coupled physical-biological model and its application to the 1996 spring plankton bloom in Prince William Sound, Alaska

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Abstract

A 3-D coupled biological-physical model of Prince William Sound was developed to simulate the spring plankton bloom of 1996. The physical model is based on a 3-D circulation model under forcing of monthly heat flux, freshwater discharge of a line source, daily wind, Alaska Coastal Current (ACC) inflow/outflow, and tide. The biological model consists of four compartments: nutrients, phytoplankton, zooplankton and detritus. A mixed layer model is introduced to calculate vertical mixing caused by wind stirring and surface cooling. The simulated spring phytoplankton bloom starting and ending time and its magnitude compare well with field observations at several layers from 0 m to 50 m at Station AFK in the sound. In the western sound, the bloom occurred earlier, but was less intensive; and the bloom depth was shallower than in the east. In the central, eastern sound and Montague Strait, the plankton blooms occurred following the bloom in the western sound, but were stronger and deeper. Thus, the phytoplankton bloom lasted longer. There was a shallower, but higher phytoplankton concentration core in the eastern sound at the beginning of the bloom, which disappeared later as the circulation changed.

1 Introduction

Prince William Sound (also refer to as the sound or PWS) is located at the southern coast of the Gulf of Alaska. It is an important hatchery place for many species, such as seabirds, mammals, salmon, herring, etc. Previous studies found
that the spring plankton bloom of the sound can be explained by the Sverdrup [3] theory during spring in high latitudes, as solar heating increases and mixing decreases. The mixed layer depth rises above the critical depth and net photosynthesis exceeds net respiration throughout the water column, enabling the phytoplankton to bloom. Thus, a responsive mixed layer model is necessary to examine the bloom, and high vertical resolution is essential to a biological model. A strong seasonal cycle and interannual variations of the plankton community of the sound are affected mainly by physical conditions (wind, surface cooling and mixed layer depth, etc.) during a relatively short critical period, e.g. from day 90 to 130 in 1996 (Eslinger et al. [1]). The spring bloom of the sound is nutrient limited.

A major biological research question was the timing and magnitude of the spring bloom of phytoplankton. The variance in the multi-year zooplankton time-series was nutrient-limited, bottom-up regulation of zooplankton by food supply (Eslinger et al. [1]), where advection, convection, and vertical mixing are significant modulators of plankton production. It is very important for a biological model to be coupled with a 3-D circulation model to include realistic advection, convection and mixing.

This study developed a coupled 3-D physical-biological model to investigate the effects of the 3-D circulation and thermohaline structure on the timing and magnitude of the spring bloom. The physical model is based on the existing 3-D PWS model (Wang et al. [5]). The biological NPZD model has one component of phytoplankton, zooplankton, nutrients and detritus, respectively.

2 Model description

The model domain includes the entire sound with two open boundaries, one at Hinchinbrook Entrance and the other at Montague Strait (Fig. 1). The details of The 3-D circulation model, its open boundary conditions, and initial temperature and salinity fields are described by Wang et al. [5]. The model forcing includes freshwater runoff of a line source, heat flux, ACC throughflow, wind, and MZ tide (Wang et al. [5]).

Figure 1: Model domain. The two lines across the Hinchinbrook Entrance and the Montague Strait are open boundaries. The thick line in the middle sound is the section discussed in Fig. 9 and Fig. 10.
The NPZD biological model consists of four compartments: nutrients, phytoplankton, zooplankton, and detritus, which are controlled by the equations:

\[
\frac{\partial N}{\partial t} = (-Gr + Resp + R_p + E_c + R_d)/C_{aw} - Adv - Diff
\]

\[
\frac{\partial P}{\partial t} = Gr - Resp - R_p - I_z - Adv - Diff
\]

\[
\frac{\partial Z}{\partial t} = I_z - E_z - E_g - M_z - Adv - Diff
\]

\[
\frac{\partial D}{\partial t} = E_z - R_d - Adv - Diff
\]

where \( N \) (mg \( N \) m\(^{-3}\)) is the nitrate + nitrite concentration; \( P \) (mg \( C \) m\(^{-3}\)) is the phytoplankton concentration; \( Z \) (mg \( C \) m\(^{-3}\)) is the zooplankton concentration; and \( D \) (mg \( C \) m\(^{-3}\)) is the detritus concentration. \( Gr \) is the phytoplankton growth rate, whose limitation factors include light and nutrients:

\[
Gr = P \mu_0 \exp(k_T T) \min\{\text{limit}_L, \text{limit}_N\}
\]

\[
\text{limit}_L = (1 - \exp(-k_a PAR / I_0)) \exp(-k_L PAR / I_0)
\]

\[
\text{limit}_N = (N - s_0) / (k_s + N - s_0)
\]

\( T \) is the water temperature from the physical model; \( \mu_0 \) is the maximum possible growth rate at \( 0^\circ \text{C} \); \( k_a \) describes the ability of the phytoplankton to absorb light; \( I_0 \) is the minimum light level at which photosynthesis begins; \( PAR \) is phytosynthetically available radiance with wavelength from 400 nm to 700 nm,

\[
PAR(z) = PAR(0)e^{-b_{at}}
\]

where \( z \) is the depth, and \( z=0 \) denotes the sea surface; \( Resp \) is the phytoplankton respiration rate; \( R_p \) is phytoplankton remineralization rate; \( I_z \) is ingestion rate of phytoplankton by zooplankton, \( E_c \) is the excretion rate of zooplankton, and \( E_g \) is egestion rate of zooplankton; \( R_d \) is the remineralization rate of detritus, and \( M_z \) is mortality rate of zooplankton. They can be expressed as:

\[
Resp = P R_0 \exp(k_T T), \quad k_{PAR} = k_0 + (k_{part} + 1)k_p P/C_{totChl},
\]

\[
R_p = P R_{m0} \exp(k_{rm} T), \quad I_z = z g r_0 \exp(k_{gr} T)(1 - \exp(C_{iv}(P_0 - P))),
\]

\[
E_c = (A_{Ef} - G_{Ef}) I_z, \quad E_g = (1 - A_{Ef}) I_z,
\]

\[
R_d = D \times r_{fp} e^{k_m T}, \quad M_z = m_{z0} \exp(k_m T) Z^2,
\]
Adv and Diff are the large-scale oceanic advection and diffusion:

\[ \text{Adv} = (u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + (w - w_s) \frac{\partial}{\partial z}) \phi \]

\[ \text{Diff} = (A_x \frac{\partial^2}{\partial x^2} + A_y \frac{\partial^2}{\partial y^2} + A_z \frac{\partial^2}{\partial z^2}) \phi \]

where \( u, v, \) and \( w \) are the 3-D sea water velocity components from the 3-D circulation model; \( \phi \) denotes any variable of \( P, N, Z \) or \( D \). Nutrient and zooplankton sinking rates, \( w_n \) and \( w_z \) are set to 0. The sinking rate of detritus \( w_a \) is set to a constant of 0.35 (m/h). The sinking rate of phytoplankton \( w_p \) is

\[ w_p = w_{max} \times \left[ 1 - \tanh \left( 0.549306N / k_g \right) \right] \]

The constants (Table 1) in the governing equations are adapted from Eslinger et al. [1].

Table 1: Values of constants used in the model equations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{A}_{Ef} )</td>
<td>0.7</td>
<td>( C_{iv} )</td>
<td>0.246 (1 mg C(^{-1}))</td>
</tr>
<tr>
<td>( C_{ioChl} )</td>
<td>40</td>
<td>( C_{ioN} )</td>
<td>5.69</td>
</tr>
<tr>
<td>( G_{Ef} )</td>
<td>0.3</td>
<td>( g_{r0} )</td>
<td>0.0125 (h(^{-1}))</td>
</tr>
<tr>
<td>( k_a )</td>
<td>0.057</td>
<td>( k_{fp} )</td>
<td>0.03 (°C(^{-1}))</td>
</tr>
<tr>
<td>( k_g )</td>
<td>0.0633 (°C(^{-1}))</td>
<td>( k_{gr} )</td>
<td>0.0693 (°C(^{-1}))</td>
</tr>
<tr>
<td>( k_i )</td>
<td>0.001316</td>
<td>( k_m )</td>
<td>0.069 (°C(^{-1}))</td>
</tr>
<tr>
<td>( k_p )</td>
<td>0.0148 (m(^{-1}) (mg chl m(^{-3}))(^{-1}))</td>
<td>( k_0 )</td>
<td>0.159 (m(^{-1}))</td>
</tr>
<tr>
<td>( k_{part} )</td>
<td>2.35428</td>
<td>( k_T )</td>
<td>0.069 (°C(^{-1}))</td>
</tr>
<tr>
<td>( k_{rm} )</td>
<td>0.03 (°C(^{-1}))</td>
<td>( k_s )</td>
<td>1.5 (mg N m(^{-3}))</td>
</tr>
<tr>
<td>( m_{p0} )</td>
<td>0.0049385 (h(^{-1}))</td>
<td>( m_{z0} )</td>
<td>0.0004283 (h(^{-1}))</td>
</tr>
<tr>
<td>( P_0 )</td>
<td>0.2447 (mg C l(^{-1}))</td>
<td>( r_0 )</td>
<td>0.003 (h(^{-1}))</td>
</tr>
<tr>
<td>( r_{fp} )</td>
<td>0.0000923 (h(^{-1}))</td>
<td>( r_{m0} )</td>
<td>0.000923 (h(^{-1}))</td>
</tr>
<tr>
<td>( s_0 )</td>
<td>0.0 (mg N m(^{-3}))</td>
<td>( w_{max} )</td>
<td>0.18 (m h(^{-1}))</td>
</tr>
</tbody>
</table>

\( A_x \) and \( A_y \) are the horizontal diffusion coefficients; \( A_z \) is the vertical diffusion coefficient, which is set to be a turbulent mixing coefficient (1 m\(^2\)/s) in the mixed layer and decreased exponentially to a molecular mixing coefficient (10\(^{-4}\) m\(^2\)/s)
under the mixed layer. The mixed layer depth is calculated at each time step using the Froude number based on the mixed layer model of Thompson [4].

Hourly buoy data at NOAA Station 46060 (location shown in Fig. 1), including wind and air temperature, were used to calculate the total sea surface heat flux:

$$Q_{tot} = Q_{solar} + Q_{rh} + Q_{alw} - Q_{sub}$$  \hspace{1cm} (11)

where $Q_{solar}$ is the solar radiation with wavelength from 250 nm to 4000 nm; $Q_{rh}$ is the sensible heat flux, $Q_{alw}$ is the latent heat flux; and $Q_{sub}$, $Q_{alw}$ are the air and water long-wave emission, respectively. The algorithm is based on Parkinson and Washington [2].

The horizontal model grid is 1.2 km for the coupled model. There are 15 vertical sigma layers for the 3-D circulation model and 33 vertical layers for the biological model (3m resolution in the upper 99m and one layer below 99m). The output of the physical model (velocity, temperature, and salinity) was interpolated to the vertical grid points of the biological model. The coupled model uses a mixed layer model to deal with the rapid changes of the mixed layer depth in response to surface warming or cooling and wind mixing. The time step is 1 hour for the biological model and 100 s for the physical model. The open boundary conditions for the biological model were specified to be no flux for all biological components.

A one-year simulation was conducted using this coupled model. Due to lack of data, the initial condition for the biological model was set to be homogeneous at each grid and each layer, similar to the Eslinger et al.'s (2001) model: $P = 20 \text{ mg C m}^{-3} = 0.5 \text{ mg Chl. m}^{-3}$; $Z = 0.2 \text{ mg C m}^{-3}$; $N = 160 \text{ mg N m}^{-3} = 11.4 \mu\text{M}$; $D = 0 \text{ mg C m}^{-3}$.

3 Model results

3.1 Physical environment

In mid-April, water temperature in the northwestern sound is warmer than water in the southeastern sound (Fig. 2a). The water is fresher in the northwest because of the addition of freshwater runoff from snow and glacier melting along the western coast (Fig. 2b). Thus, the surface water stratification occurs earlier in the west than in the east. There are anticyclonic cyclonic gyres in the central sound and small gyres in the northeastern sound (Fig. 2c). In the western sound, water flows from north to south, and exits through Montague Strait.

Figures 3a-d show the measured hourly air temperature, wind speed, water temperature, and calculated daily mean net sea surface heat flux (including short/long wave radiation and latent/sensible heat flux), respectively, at Station 46060. In addition to a diurnal cycle, the air temperature starts to rise steadily after day 94. At this time, the daily mean net sea surface heat flux also becomes positive and increases with time. This provides a physical environment to the beginning of the phytoplankton spring bloom. The wind was strong during days 95 to 100, after which the wind was calm. Sea surface temperature increased
slowly with time and there were fluctuations between days 102 to 106 that might be caused by advection because there was no significant fluctuation of wind, air temperature, or surface heat flux during the same period.

Figure 2: Sea surface temperature (a), salinity (b), and current (c) on April 16.

Figure 3: Hourly air temperature (a), wind speed (b), water temperature (c), and daily net sea surface heat flux (c) at Station 46060.
3.2 Spring phytoplankton bloom

The simulated chlorophyll \( a \) at 10 m and the average of 25-50 m (Fig. 4a and 4b) compares well with observations at Station AFK (location shown in Fig. 1). The bloom started on day 97, reached the peak of 22 mg/m\(^3\), remained at a high from day 99-121, and ended on day 122 for a total bloom period of 25 days. The bloom averaged over 25-50 m denotes an average across the thermocline. The bloom in this layer had a slight delay, when compared with the surface layer. The peak was lower. The simulated start timing and the peak value of the bloom at 25-50 m compare well with the field observations. However, the observed data show a faster decline than the modeled results. The observed data also show a second peak at day 114 to 116, especially at depth 25-50 m. This peak was not captured by the model, because there was no meteorological data at Station AFK, and we had to use the meteorological data at NOAA Station 46060, which is located in the central sound. Since Station 46060 is in the open sea and Station AFK is in a narrow strait channeled by mountains, the differences of meteorological conditions between the two stations can cause the discrepancy in the modeled vertical mixing that brings up more nutrients to support a second bloom peak.

The modeled and observed N + N in the 0-25 m layer (Fig. 5a) at Station AFK started to decrease earlier and sharper than that in 25-50 m layer (Fig. 5b). This means that the phytoplankton bloom occurred mainly in the upper 25 m. After the bloom, the modeled nutrient remained low, but the observed nutrient increased. Those nutrients should have originated from the Alaska coastal water outside the sound. The modeled nutrients at 25-50 m is close to the observed, but did not increase after the bloom.

![Figure 4](image)

**Figure 4**: Observed (solid) and calculated (dashed) chlorophyll \( a \) concentration at depth of (a) 10 m, (b) the mean of 25-50 m at Station AFK.

![Figure 5](image)

**Figure 5**: Comparison of observed (solid) and calculated (dashed) nutrient concentration at depth of (a) 0-25 m, and (b) 25-50 m at Station AFK.
Figure 6: Modeled (dashed, left y-axis) and observed (solid, right y-axis) zooplankton averaged from 0 to 50 m at Station AFK.

Figure 7: Simulated time series of surface 25m averaged nutrients (a), chlorophyll a (b), zooplankton (c), and detritus (d).

The zooplankton was collected at Station AFK by recording the settled volume of zooplankton to the nearest ml (milliliter) and by rebottling individual samples for processing. The settled volumes were converted to biomass using a factor of 0.7 g wet weight ml\(^{-1}\) (Wiebe et al [6]). Because the modeled zooplankton has a different unit from the observed data, we drew two y-axes with different units to combine the modeled and observed zooplankton into one plot (Fig. 6). The comparison of the modeled and observed zooplankton averaged in the upper 50m at Station AFK displays a similar trend that zooplankton kept rising up in the water column from the beginning of phytoplankton bloom.

Figures 7a-d show the time series of the modeled upper 25m averaged N + N, chlorophyll a, zooplankton, and detritus over the entire sound. Chlorophyll a concentration increased from day 94 to a maximum of 22 mg/m\(^3\) around day 102, and started to decline after day 107. The bloom ended after day 120 (Fig. 7b). Nitrate + nitrite concentration (Fig. 7a) were high before the bloom and were rapidly depleted. Zooplankton biomass (Fig. 7c) increased steadily throughout the bloom. Detritus also showed a continuous increase, reached a maximum around day 125, and then sharply declined because of the sinking of phytoplankton and detritus.
3.3. **Horizontal and vertical structures of the phytoplankton bloom**

The simulated phytoplankton averaged over the upper 25m on April 7 and 10 (Fig. 8) showed horizontal differences of the phytoplankton bloom in the sound. The bloom in the western sound occurred on April 7, which was earlier than the bloom in the eastern sound, because the surface water was warmer and fresher in the western sound (Fig. 2a and 2b). April 10 was the peak of the spring bloom. Phytoplankton biomass in the eastern sound was higher than that in the west because the eastern sound had a deeper mixed layer and stronger vertical mixing to bring up the nutrients below the mixed layer.

**Figure 8:** Upper 25m-averaged phytoplankton on April 7 (a) and April 10 (b).

The cross-section (the thick line in Fig. 1) view of nutrient and phytoplankton on April 7 (Fig. 9) showed the vertical structure of the nutrient and phytoplankton during the bloom. The phytoplankton bloom in the west began earlier than in the east, particularly in the water with a shallower mixed layer. However, the bloom was shallower in the west due to strong vertical stratification that prevents vertical mixing. In the central sound there was a core of high phytoplankton biomass, where the mixed layer was relatively shallow and phytoplankton biomass was high.

Strong vertical mixing was evident on April 13 (Fig. 10a, b) compared to April 7 (Fig. 9a, b). Vertical mixing was caused by large fluctuations of surface water temperature (Fig. 3c). In the central and eastern sound, the maximum mixed layer depth reached 55 m. In the western sound, the mixed layer depth increased from west to east. Vertical mixing played a very important role on bringing more nutrients from beneath the mixed layer to the euphotic zone that extended the bloom period. After the mixed layer returned to normal, all the nutrients brought up from the lower layer supported the bloom, which lasts longer than the western sound.
4 Conclusion

The model successfully simulated the spring phytoplankton bloom of PWS in 1996. The modeled timing (starting and ending) and the magnitude of the spring bloom compare reasonably well with observed data at several depths over a 50 m water column at Station AFK in Elrington Passage. The spring phytoplankton bloom began in early April when the surface water absorbed solar heating and the mixed layer became shallow. Another favorable factor promoting the spring bloom was that ACC throughflow in April was at its minimum in 1996 (Wang et al. [5]). This prevented the phytoplankton from massively flowing out of the sound. Thus, the phytoplankton produced in the spring bloom could be retained in the central and eastern sound, and Montague Strait, to support overwintering zooplankton. Geographical differences of the phytoplankton bloom exist because of the differences of the temperature and salinity fields in the sound. The circulation pattern in the sound was important to redistribute the phytoplankton biomass. Vertical mixing played an important role in bringing nutrients from below the mixed layer, which extended the duration of the bloom.

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References
